



Study and Investigation on the Development and Environmental Evaluation of Coconut Oil–Hybrid Nanofluid for Sustainable MQL Turning of EN24 Steel



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Abstract: The demand for environmentally sustainable machining has driven the search for cutting fluids that combine high cooling–lubrication efficiency with biodegradability. This work reports the synthesis and characterization of a coconut-oil–based hybrid nanofluid containing Aluminum Oxide (Al_2O_3 , 0.75 vol.%) and Copper Oxide (CuO , 0.25 vol.%) stabilized with 1 wt.% Sodium Dodecyl Sulfate (SDS) for Minimum Quantity Lubrication (MQL) applications. The nanofluid was prepared by a two-step method (magnetic stirring and ultrasonication) and evaluated for dispersion stability, thermal resistance, chemical interactions, and environmental impact. Zeta potential analysis showed strong colloidal stability (–38.2 mV). Fourier Transform Infrared Spectroscopy (FTIR) confirmed effective surfactant–nanoparticle bonding. Thermogravimetric Analysis (TGA) revealed high thermal stability with initial degradation around 100°C and only % mass loss at 200°C. Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) testing yielded a BOD/COD ratio of 0.57, indicating ready biodegradability. These results suggest that the developed Al_2O_3 – CuO hybrid nanofluid in coconut oil is a thermally stable, eco-friendly alternative to mineral oils, and it shows strong potential for green manufacturing and sustainable MQL turning of hard-to-machine steels, such as EN24.

Introduction

Manufacturing industries are under growing pressure to adopt environmentally sustainable machining practices while maintaining high productivity and product quality (Kamaruddin et al., 2020). Cutting fluids are widely used to reduce friction, cool the cutting zone, and extend tool life, but conventional flood cooling systems consume large fluid volumes, generate hazardous waste, and pose health and environmental risks (Liu et al., 2023). Minimum Quantity Lubrication (MQL) has emerged as a promising alternative, using a small amount of fluid (typically <50 mL/h) to provide effective cooling and lubrication exactly where needed, while significantly reducing waste and operating cost (Matuszak et al., 2023).

To enhance the performance of MQL fluids, researchers have increasingly explored nanofluids stable suspensions of nanoparticles in base oils that offer improved thermal conductivity, lubricity, and wear resistance (Mishra et al., 2020). Among nanoparticles, aluminum oxide (Al_2O_3) is valued for its hardness, chemical stability, and tribological performance, while copper oxide (CuO) exhibits superior thermal conductivity, promoting rapid heat removal from the cutting zone (Najiha et al., 2020). Combining these in a hybrid nanofluid can exploit their complementary properties, achieving enhanced cooling and anti-wear characteristics (Sahoo et al., 2021).

Equally important is the choice of base fluid. Biodegradable vegetable oils, particularly coconut oil, have attracted interest due to their renewable nature, high



lubricity, low toxicity, and environmental compatibility compared with mineral oils. However, vegetable oil-based nanofluids face challenges such as particle agglomeration and settling, which can reduce their effectiveness (Zhang & Cao, 2023). The use of surfactants such as sodium dodecyl sulfate (SDS) helps stabilize nanoparticles by reducing surface tension and promoting uniform dispersion (Boswell et al., 2017).

Although studies have investigated individual Al_2O_3 or CuO nanofluids in vegetable oils, systematic research on coconut oil-based hybrid Al_2O_3 -CuO nanofluids remains limited. Previous work has largely focused on synthesis and basic biodegradability testing, with insufficient attention to thermal stability, surfactant-particle interactions, and dispersion characterization, all of which are critical for reliable performance in MQL machining of hard-to-cut materials such as EN24 alloy steel (Iyappan & Ghosh, 2019). Furthermore, while biodegradability (e.g., BOD/COD ratio) has been reported, other key sustainability indicators such as energy reduction, tool-life extension, and eco-impact of nanofluid usage remain underexplored (Khan et al., 2019).

This study aims to bridge these gaps by:

1. Synthesizing a coconut oil-based hybrid nanofluid containing 0.75 vol.% Al_2O_3 and 0.25 vol.% CuO stabilized with 1 wt.% SDS using a two-step method.
2. Evaluating dispersion stability through zeta potential, confirming chemical interactions via Fourier Transform Infrared Spectroscopy (FTIR), and assessing thermal resistance with Thermogravimetric Analysis (TGA).
3. Investigating environmental sustainability using Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) tests to establish biodegradability.

By integrating nanofluid design, advanced characterization, and environmental evaluation, this work supports the development of eco-friendly, thermally stable cutting fluids suitable for green manufacturing and MQL turning of EN24 steel (Manoj Kumar & Ghosh, 2015; Kamata & Obikawa, 2007; Nath et al., 2025; Nath and Xavier, 2025; Pramanik et al., 2025).

Materials and Methods

Materials

Virgin coconut oil (food-grade) was selected as the base fluid because of its biodegradability, non-toxicity, renewable origin, and inherent lubricating ability (Ganguly et al., 2025; Mia et al., 2018)). Two types of nanoparticles were used:

- a) Aluminum oxide (Al_2O_3): average particle size 20–50 nm; selected for high hardness, wear resistance, and tribological stability.
- b) Copper oxide (CuO): average particle size 30–50 nm; chosen for its high thermal conductivity (~33 W/mK), which enhances heat removal during machining.

A surfactant, sodium dodecyl sulfate (SDS), was added at 1 wt.% to lower surface tension and maintain long-term nanoparticle dispersion. The prepared nanofluids were later applied in Minimum Quantity Lubrication (MQL) turning of EN24 alloy steel, a hard-to-machine material widely used in automotive and aerospace components.

Nanofluid Preparation

A two-step dispersion method was employed to obtain homogeneous and stable suspensions (Figure 1):

1. Weighing:
 - ⇒ Al_2O_3 nanofluid: 0.75 g Al_2O_3 dispersed in 100 mL coconut oil.
 - ⇒ CuO nanofluid: 0.25 g CuO dispersed in 100 mL coconut oil.
 - ⇒ Hybrid nanofluid: 0.75 g Al_2O_3 + 0.25 g CuO dispersed in 100 mL coconut oil
2. Surfactant addition: 1 wt.% SDS was added to each mixture to prevent agglomeration and enhance nanoparticle wetting.
3. Magnetic stirring: Each suspension was stirred at ~600 rpm for 2 h to achieve preliminary dispersion.
4. Ultrasonication: Probe/bath ultrasonication at 40 kHz for 60 min broke down agglomerates and promoted uniform distribution of nanoparticles (Somavanshi & Sathe, 2023).
5. Stability check: Prepared fluids were stored undisturbed at room temperature for 7 days to observe sedimentation; the hybrid sample remained visually stable (An & Dang, 2019).



Figure 1. Prepared nanofluid samples: (a) Al_2O_3 in coconut oil, (b) CuO in coconut oil, (c) hybrid Al_2O_3 -CuO (0.75 % + 0.25 %) in coconut oil.

Results and Discussion

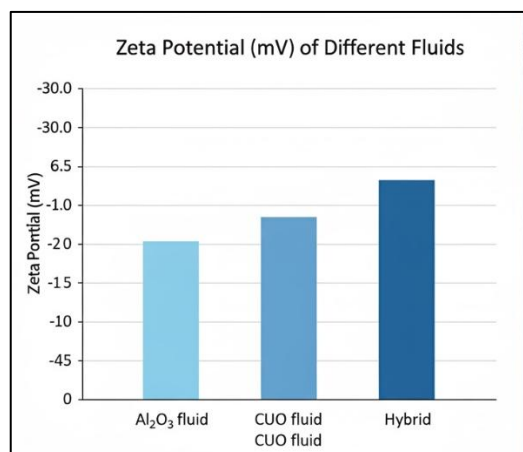
Dispersion Stability (Zeta Potential)

The zeta potential values of the prepared nanofluids are presented in Table 1. Both single nanoparticle suspensions (Al_2O_3 and CuO) showed a substantial increase in electrostatic stability compared with typical vegetable oil without nanoparticles. The hybrid Al_2O_3 – CuO nanofluid exhibited the most negative potential (-38.2 mV), which is well below the -30 mV threshold generally accepted as the limit for good colloidal stability (Kuo *et al.*, 2019). This indicates that the combined effect of SDS surfactant and the hybrid nanoparticle system provides strong electrostatic repulsion between particles, preventing agglomeration and sedimentation. Such stability is essential for consistent delivery in MQL applications, avoiding nozzle clogging and ensuring uniform cooling and lubrication (Sen *et al.*, 2019).

Table 1. Zeta potential of prepared nanofluids.

Sample	Zeta Potential (mV)
Al_2O_3 fluid	-35.1
CuO fluid	-33.4
Hybrid	-38.2

All samples showed zeta potential values greater than 30 mV, confirming good electrostatic stability. The hybrid formulation achieved the highest stability (-38.2 mV), attributed to the synergistic interaction between Al_2O_3 and CuO particles and the strong adsorption of SDS molecules on their surfaces.



Graph 1. Zeta Potential Analysis.

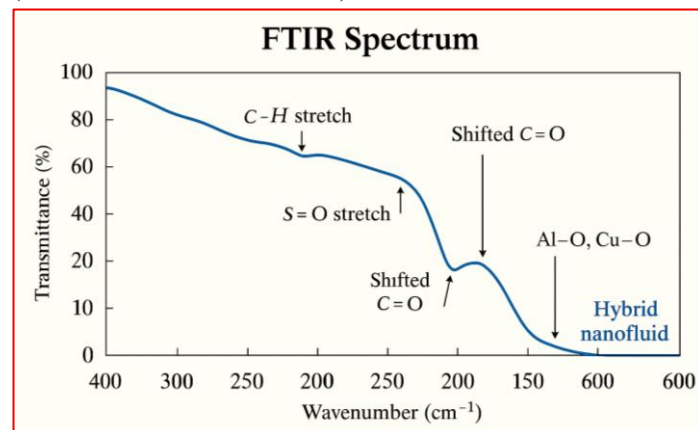
FTIR Analysis

The FTIR spectra confirmed effective interaction between the coconut oil base fluid, SDS surfactant, and nanoparticles:

- ⇒ Peaks at 2922 cm^{-1} and 2852 cm^{-1} correspond to the C–H stretching vibrations of the oil.
- ⇒ A strong band at $1040\text{--}1090\text{ cm}^{-1}$ corresponds to S=O stretching, confirming the presence of SDS.

- ⇒ Distinct absorptions in the $550\text{--}650\text{ cm}^{-1}$ range represent Al–O and Cu–O bonds from the nanoparticles.
- ⇒ The C=O ester peak shifted from its normal position ($\sim 1740\text{ cm}^{-1}$) to 1730 cm^{-1} in the nanoparticle suspensions, indicating chemical interaction and adsorption of SDS on the nanoparticle surfaces.

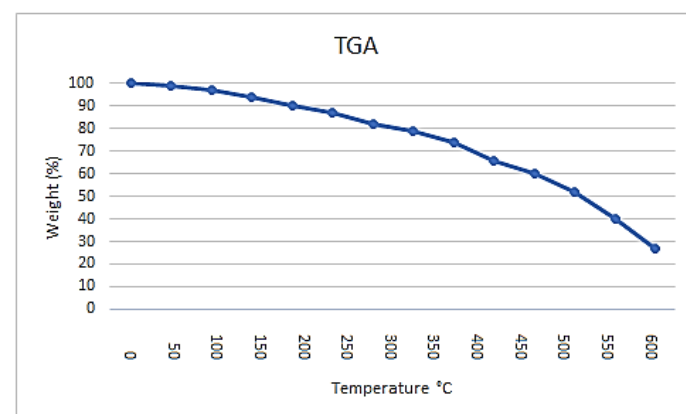
The observed peak shifts demonstrate that SDS molecules successfully coated nanoparticles, forming a stabilizing layer that reduces surface energy and enhances long-term suspension stability. This explains the high zeta potential values measured for the hybrid nanofluid (Somavanshi & Sathe, 2024).



Graph 2. FTIR Analysis.

Thermogravimetric Analysis (TGA)

Thermogravimetric analysis results are summarized in Table 2. Both single-particle fluids exhibited improved thermal stability compared with base vegetable oils reported in literature. The hybrid nanofluid showed the highest stability, with degradation starting only around 320°C and 27 % residual mass at 600°C .



Graph 3. Thermogravimetric analysis (Hybrid Al_2O_3 - CuO).

The thermogravimetric analysis of the hybrid nanofluid (Al_2O_3 0.75 % + CuO 0.25 %) shows that it experiences only about 10% weight loss up to 200°C , primarily due to the evaporation of light volatiles and the initial decomposition of organic components in the

coconut oil base. Major thermal degradation begins at approximately 320 °C, indicating that the fluid can easily tolerate the cutting temperatures of 200-300 °C typically encountered during Minimum Quantity Lubrication (MQL) turning of hard-to-machine steels such as EN24 without breaking down prematurely. Above 320 °C the weight decreases gradually, leaving about 27 % non-volatile residue at 600 °C; this residue consists mainly of the inorganic Al_2O_3 and CuO nanoparticles along with thermally stable carbonaceous compounds. The delayed onset of degradation and higher final residue compared with plain vegetable oils reported in the literature (often less than 15 % residue at 600 °C) confirm the enhanced thermal stability of the hybrid formulation. This improved performance is attributed to the synergistic effect of Al_2O_3 , which provides mechanical and tribological stability, and CuO , which offers high thermal conductivity, combined with SDS surface modification that maintains a stable dispersion. Overall, the hybrid Al_2O_3 – CuO nanofluid demonstrates excellent thermal resistance, making it well-suited for sustainable MQL machining where elevated cutting temperatures are common.

Environmental Assessment (BOD/COD)

The biodegradability of the prepared nanofluids is shown in Table 2. All fluids maintained a BOD/COD ratio >0.5 , classifying them as readily biodegradable.

Table 2. Biodegradability assessment of prepared fluids.

Fluid	BOD/COD
Al_2O_3 fluid	0.59
CuO fluid	0.53
Hybrid	0.57

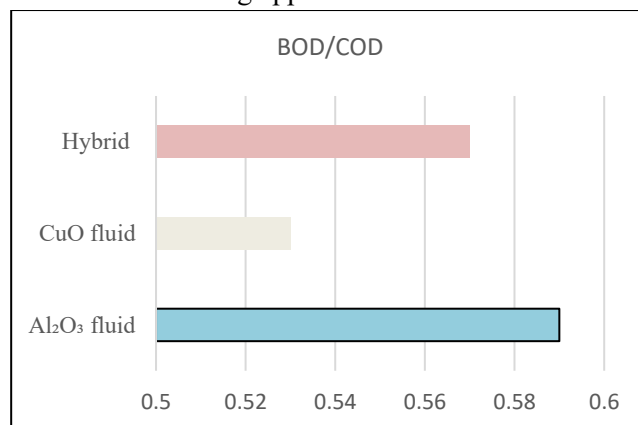
The biodegradability results in Table 3 show that all three nanofluids remain readily biodegradable, as their BOD/COD ratios exceed the 0.50 threshold typically used to classify fluids as environmentally acceptable.

The Al_2O_3 fluid achieved the highest ratio (0.59), indicating the greatest proportion of biologically degradable organic matter among the three samples.

The hybrid nanofluid also maintained a high ratio (0.57), demonstrating that the combined addition of Al_2O_3 and CuO does not significantly compromise biodegradability.

The CuO fluid recorded a slightly lower value (0.53), which is expected because copper oxide is denser and contributes a larger inorganic fraction that does not biodegrade.

Nevertheless, even this value remains above 0.50, confirming that all the prepared fluids satisfy the “readily biodegradable” criterion and can be considered eco-friendly alternatives to mineral-oil cutting fluids for sustainable machining applications.



Graph 4. Biodegradability assessment.

Conclusion

This study successfully developed and characterised a coconut oil-based hybrid nanofluid containing Al_2O_3 (0.75 vol.%) and CuO (0.25 vol.%) stabilised with 1 wt.% SDS for sustainable Minimum Quantity Lubrication (MQL) machining. The nanofluid exhibited excellent dispersion stability with a zeta potential of -38.2 mV, confirmed chemical interaction and surfactant anchoring through FTIR, and demonstrated superior thermal resistance, delaying major degradation until about 320 °C with 27 % residue remaining at 600 °C. Environmental assessment showed a BOD/COD ratio of 0.57, confirming that the fluid remains readily biodegradable and environmentally safe compared to conventional mineral oils.

Overall, the hybrid Al_2O_3 – CuO nanofluid shows a balanced combination of stability, high-temperature performance, and eco-friendliness, making it an excellent alternative cutting fluid for green and sustainable MQL turning of hard-to-machine steels such as EN24. Future work can focus on optimising cutting parameters using RSM and evaluating real machining performance metrics such as tool wear, surface finish, and energy efficiency.

Future Scope

Although the present work demonstrates the potential of a coconut oil-based hybrid Al_2O_3 – CuO nanofluid for Minimum Quantity Lubrication (MQL) machining, several directions remain for future investigation:

1. **Machining Performance Optimization:** Apply Response Surface Methodology (RSM) optimization tools to fine-tune cutting speed, feed, and depth of cut for maximum tool life, minimum surface roughness, and reduced cutting temperature.

2. Long-Term Stability Studies: Evaluate nanofluid stability over extended storage periods and under continuous recirculation in MQL systems to ensure consistent dispersion and avoid nozzle clogging.
3. Alternative Surfactants & Additives: Explore bio-based or less foaming surfactants and functional additives to further improve dispersion, lubricity, and oxidation resistance.
4. Extended Material Applications: Test the hybrid nanofluid on other difficult-to-machine alloys such as Inconel, titanium, or hardened tool steels to validate its broader industrial applicability.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this research paper.

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